Chapter 5

Prospects for Renewable Energy: Meeting the Challenges of Integration with Storage

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Chapter Outline

INTRODUCTION

Rapid growth in renewable energy generation has been spurred by concerns such as energy security, fuel diversity, and climate change. Most major economies have government policies supporting renewable electricity. Seventeen countries currently have feed-in tariffs, ten countries have quota obligation systems with tradable green certificates, and four countries have tender systems [1]. In the United States, 36 states and the District of Columbia have set specific standards or goals for a certain percentage of electric power generation and sales to come from renewable sources [2], and utilities in 48 states now offer their customers the option to purchase green power [3].

Lower costs associated with wind turbines and solar cells due to technology advancements and economies of scale have also contributed to the accelerated growth of these energy markets, notably during the past five years. In 2009,

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a record 10 GW of new wind power was installed in the United States, resulting in cumulative wind installations of 35 GW [4]. Following the same trend, total U.S. solar electric capacity from photovoltaic (PV) and concentrating solar power (CSP) technologies exceeded 2 GW in 2009, with 1.65 GW being grid-tied. The residential PV market doubled and three new CSP plants were built, resulting in a 37% increase in annual installations over 2008 from 351 MW to 481 MW [5].

As renewable energy technologies mature, and with continued financial subsidies, they are expected to provide a growing share of the world's electricity requirements. Figure 5.1 shows the global growth of renewables compared to other types of generation projected to 2035. Currently, solar PV is the fastest growing renewable technology worldwide at an average of 60% per year, followed by wind power at 27% and biofuels at 18% [1]. However, concerns about potential impacts of high penetration of renewables on the stability and operation of the electric grid may create barriers to their future expansion. The intermittent and variable nature of renewable sources, particularly wind and solar, poses reliability concerns that must be addressed at higher penetration levels. As other chapters in this volume explain, our existing grid is not designed to deal with these types of renewable resources. Current industry practices need to be altered and a smart grid needs to develop for the successful integration of renewables.

Energy storage can serve as an enabling technology for renewables integration by allowing for output firming and dispatchability, as well as other benefits such as load shifting and peak shaving. Renewable energy technologies such as CSP systems have built-in thermal energy storage to extend the generation period beyond the peak solar incidence. A study by the National Renewable Energy Laboratory (NREL) found that even for low penetration levels, adding

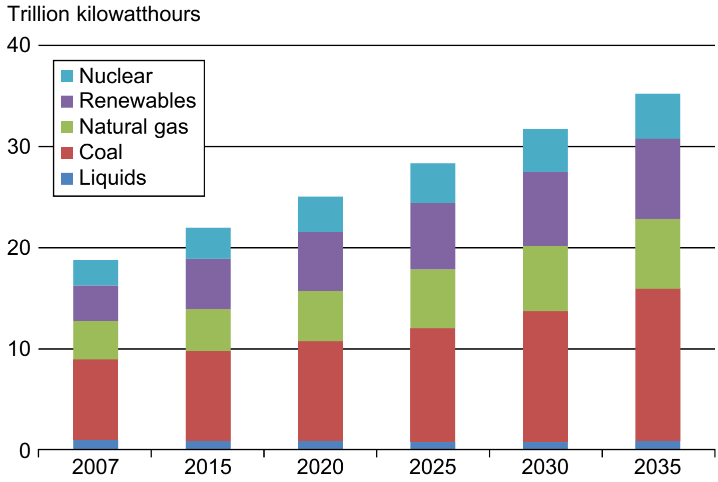

FIGURE 5.1 World electricity generation by fuel, 2007–2035. *(Source: US Energy Information Administration, "International Energy Outlook 2010," http://eia.gov/oiaf/ieo/)*

thermal energy storage can significantly increase the value of CSP through generation shifting, in some cases outweighing the costs of storage [6]. Other technologies such as PV and wind will require a variety of energy storage technologies to help offset their intermittent generation.

This chapter focuses on integration issues surrounding solar power since wind integration is covered in several other chapters. A discussion follows on the possible solutions to these issues using energy storage, which is applicable to the integration of both wind and solar resources. This chapter focuses on storage technologies since Chapters 9 and 10 cover demand response and direct load control for providing capacity firming and ancillary services, and Chapters 18 and 19 cover electric vehicles for reducing wind integration costs in different markets.

The chapter is organized into four sections. Section "High Penetration of Renewables" covers the benefits and issues associated with the high penetration of renewables, focusing on PV, into the electric grid. Section "Energy Storage for Integration" discusses the role of energy storage in mitigating these issues, including how different storage technologies are suited for specific applications. Section "Federally Funded Energy Storage Efforts" highlights research, development, and demonstrations of grid-scale energy storage supported through federal grants and the Department of Energy (DOE). The chapter's main insights are in the concluding section.

HIGH PENETRATION OF RENEWABLES

Benefits

The environmental, economic, and energy security benefits from renewable generation are magnified by increasing its penetration level, that is, the capacity of renewable generation as a percent of peak or total load. To identify these benefits and facilitate more extensive adoption of renewable distributed electric generation, the DOE launched the Renewable Systems Interconnection (RSI) study in 2007. The 15 study reports address a variety of issues related to utility planning tools and business models, new grid architectures and PV systems configurations, and models to assess market penetration and the effects of high-penetration PV systems. As a result of this effort, the Solar Energy Grid Integration Systems (SEGIS) Program was initiated in early 2008. SEGIS is an industry-led effort to develop new PV inverters, controllers, and energy management systems that will greatly enhance the benefits of distributed PV systems.

According to the RSI report on "Photovoltaics Value Analysis," the largest benefits are in cost savings from avoided central power generation and capacity, deferred or avoided transmission and distribution (T&D) investment, and lower greenhouse gas and pollutant emissions [7]. Chapter 7 of this text presents a modeling study that also arrives at similar conclusions: benefits from increased renewable integration arise from reductions in capital expenditure, fuel costs, operation and maintenance costs, and carbon costs. During most hours, with the exception of peak hours, less than 50% of the electricity system capacity is utilized. Thus, a significant portion of the network assets have been built to meet only a few hundred hours of peak demand each year. Consequently, a PV system that produces a high share of its output during on-peak hours and displaces a peaking plant will have a higher benefit.

The RSI study on "Production Cost Modeling for High Levels of Photovoltaics Penetration" found that in the western United States, PV displaces natural gas at low penetration and begins to displace coal at higher penetration [8]. Various strategies to increase production during peak demand periods and increase the benefit from this value include integrating energy storage into the PV system and integrating load management applications with the PV system controls, as schematically illustrated in Figure 5.2.

In addition to cost savings from avoided central generation, there are T&D benefits. Since PV systems can be installed on rooftops and on undesirable real estate, such as brown fields, they can reduce a utility's need to acquire land for construction of new, large-scale generating facilities. Furthermore, locations with congested transmission and/or distribution systems that typically require expensive upgrades could defer these upgrades when PV systems are installed to reduce congestion. The value of deferred T&D upgrades is estimated to be 0.1 to 10 cents/kWh, depending on factors such as location, temperature, and load growth [7].

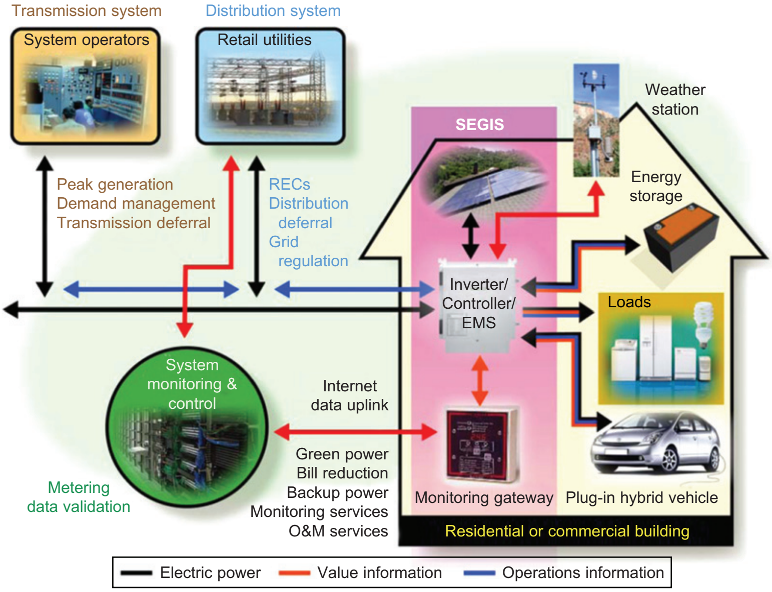

FIGURE 5.2 SEGIS diagram showing the integration of PV with the smart grid. *(Source: US DOE, http://www1.eere.energy.gov/solar/images/segis.jpg)*

Outlook

Government support for renewables has driven their growth across the world in the past decade. In 2010, China outpaced Europe and North America in wind installations by adding approximately 17 GW, becoming the global leader in terms of installed capacity. However, there has been a delay of several months in connecting this capacity to the grid. China is also the leading hydropower producer, followed by the United States, Brazil, Canada, and Russia. For solar PV capacity, Germany remains the leader and is followed by Spain and Japan. The most geothermal power is produced by the United States, followed by the Philippines, Indonesia, Mexico, and Italy. Figure 5.3 shows the current and projected mix of renewable generation (excluding hydropower) for the United States and the world, assuming a business-as-usual scenario in which

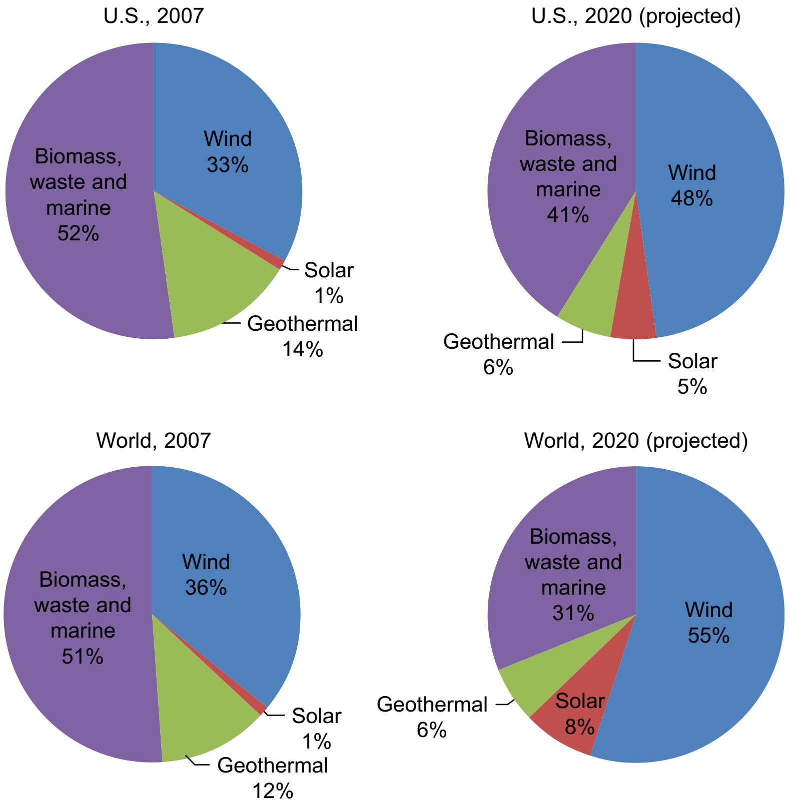

FIGURE 5.3 Renewable generation mix, excluding hydropower, for the United States and the world. *(Data for charts from US Energy Information Administration, International Energy Outlook 2010, Reference Case Projections for Electricity Capacity and Generation by Fuel, DOE/EIA-0484 (2010))*

current regulations and technological trends are maintained. For both the United States and the world, wind and solar are projected to become the majority share of renewable generation as geothermal, biomass, waste, and marine generation lose their current dominance by 2020.

There is considerable room for growth as the ultimate resource potential of wind and solar has barely been tapped to date. Land-based wind, the most readily available for development, totals more than 8,000 GW of potential capacity in the United States alone. The capacity of CSP is nearly 7,000 GW in seven southwestern states, and the generation potential of PV is limited only by the land area devoted to it, which is 100–250 GW/100 km^2 in the United States [9]. However, cost is an issue with all renewable generation. Most solar resources are in the Southwest, and wind resources are most abundant in remote locations with sparse transmission lines.

The DOE goal is to obtain 20% of U.S. electricity capacity, around 200 GW, from distributed and renewable energy sources by 2030 [10]. As of 2009, renewable generation, excluding hydropower, accounted for 3.6% of the U.S. electricity supply, with 51% of that share from wind, 10% from geothermal, 0.6% from solar, and the remainder from wood and biomass [11]. Policy developments at both the federal and state level, coupled with technology improvements funded by the DOE's SunShot Initiative,[1] are helping to create a more receptive marketplace for PV in the United States. The DOE SunShot Initiative aims to make solar energy technologies cost-competitive with other forms of energy by reducing the cost of solar energy systems by about 75% before 2020. By lowering the installed price of utility-scale solar energy to $1/W, which would correspond to roughly 6 cents/kWh, solar energy will be cost-competitive with fossil-fuel-based electricity sources without any subsidies, thereby enabling rapid, large-scale adoption of solar electricity across the United States.

Indeed, scenarios developed as part of the RSI study on “Rooftop Photovoltaics Market Penetration Scenarios” indicate that annual installations of grid-tied PV in the United States could reach 1.4–7.1 GW by 2015, resulting in a cumulative installed base of 7.5–24 GW by 2015 [12]. This study found that the variables with the largest impact on market penetration of rooftop PV were system pricing, net metering policy, extending the commercial and residential federal tax credits to 2015, and interconnection policy (Figure 5.4). Lifting net metering caps and establishing net metering had significant effects on projected PV market penetration in some states. In fact, the projected cumulative installed PV in 2015 increased by about 4 GW. Extension of the federal investment tax credit (ITC) had a critical effect on the PV market and was found to be a prerequisite for the overall success of PV in the marketplace. The projected cumulative installed PV in 2015 increased by 5 GW from a partial to full extension of the ITC.

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[1] http://www1.eere.energy.gov/solar/sunshot/

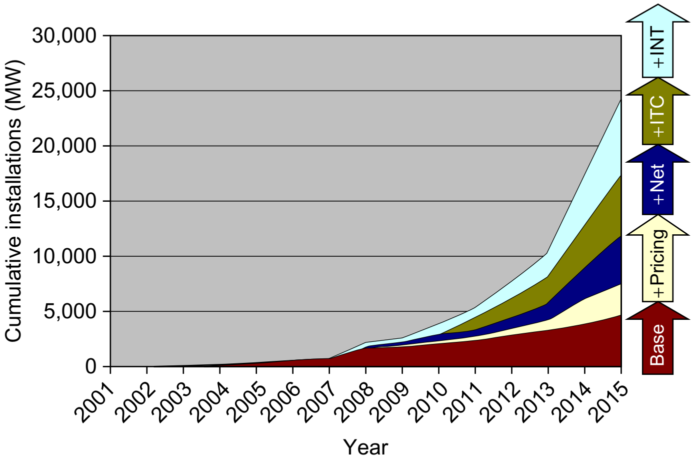

FIGURE 5.4 Influence of system pricing, net metering policy, federal tax credits, and interconnection policy on cumulative rooftop PV installations. *(Source: Paidipati et al. [12] (NREL))*

To address pricing and technology issues, the Solar Energy Technologies Program (SETP), within the DOE Office of Energy Efficiency and Renewable Energy (EERE), conducts research, development, demonstration, and deployment activities to accelerate widespread commercialization of clean solar energy technologies. The goals of the SETP are to make PV cost-competitive across the United States by 2015 and to directly contribute to private sector development of more than 70 GW of solar electricity supplied to the grid to reduce carbon emissions by 40 million metric tons by 2030. The SEGIS awards under this program engage industry/university teams in developing advanced inverters/controllers that integrate a broad range of PV system capacities from <1 kW to >100 kW with the electric grid to meet varying residential, commercial, and utility application needs.

On an international scale, most countries with significant solar installations have national solar missions or programs that set targets and an integrated policy. Several countries have PV feed-in tariffs, which actually had to be reduced in the Czech Republic, Spain, France, Italy, and Germany during 2010 and early 2011 due to unexpected rapid growth in PV deployment that increased policy cost. Capacity expansion was even suspended in some cases. Therefore, more sustainable policies need to be designed that can accommodate the decreasing cost of solar technology.

Besides cost and policy issues, codes, standards, and regulatory implementation are also major barriers to high penetration of grid-tied PV. In the United States, the electric grid safety and reliability infrastructure is governed by linked installation codes, product standards, and regulatory functions such as inspection and operation principles. The National Electric Code, IEEE standards, American National Standards, building codes, and state and federal regulatory inspection and compliance mandates must be consistent to result in a safe and reliable electric grid. Effectively interconnecting distributed renewable energy systems requires compatibility with the existing grid and future smart grid. Uniform requirements for power quality, islanding protection, and passive to active system participation could facilitate the high penetration of PV. National requirements for power quality and active participation of such renewable generation in power system operation must be developed.

As PV technology advances and becomes more competitive, it is expected to supply more residential and commercial loads at the customer's side of the meter. Therefore, PV is being developed in accordance with codes and standards that govern distributed generation, such as IEEE 1547 and UL 1741. These standards, however, are being developed on the important assumption of the low penetration of distributed generation and are focused on simplifying installations for passive system participation. They result in an electric grid that is not designed for a two-way flow of power, especially at the distribution level. The traditional planning process does not consider variable generation such as PV; therefore, the initial response of the electric industry was to exclude it from capacity planning. Current industry practices need to be altered to accommodate the high penetration of renewable generation.

As discussed in the RSI report on "Power System Planning: Emerging Practices Suitable for Evaluating the Impact of High-Penetration Photovoltaics," the emerging practice is to include renewable energy supply early in the planning process and consider it during energy growth forecasts [13]. This practice treats variable renewable generation as a part of the load and thus allows for its full integration into the planning process. In order to forecast effectively, smart grid tools must be able to accurately estimate resource data on wind and solar availability for a given location and time. Dynamic models should be able to include the impacts of resource variability such as cloud cover and wind gusts.

The operational flexibility of the balance of generation portfolio is strategically important so as not to curtail renewable generation. Planning for generation flexibility deals with two aspects of frequency control: economic re-dispatch of units every five minutes (load following) and automatic generation control (regulation). Both aspects should be evaluated relative to the net load. Understanding the load-following and regulation capabilities of the system is important in determining the system's response to load changes and in evaluating its ability to maintain the frequency within the desired control range. Having spatially diverse renewable resources and energy storage at high penetrations can reduce net load variability at the time scale of load following.

Integration Issues

Resource Intermittency

As mentioned earlier, one important challenge associated with intermittent renewable energy generation is that the generation's power output can change rapidly over short periods of time. Wind and solar generation intermittency can be of short duration or diurnal. The most common causes of short-duration intermittency are gusty conditions and clouds. As a cloud passes over solar collectors, power output from the affected solar generation system drops. Location-specific shading caused by trees and buildings can also cause relatively short-duration intermittency. During these events, the rate of change of output from the solar generation can be quite rapid. These changes in solar irradiance at a point can be more than 60% of the peak irradiance in just a few seconds. However, the time it takes for a passing cloud to shade an entire PV system depends on its speed and height, as well as the PV system size. For PV systems around 100 MW, it will take minutes rather than seconds to shade the system [14]. The resulting ramping increases the need for highly dispatchable and fast-responding generation such as peaker plants or alternatively energy storage to fill in during the decrease in output.

Diurnal intermittency is more predictable, being mostly related to the change of insolation throughout the day as the sun rises in the morning and descends in the evening. During the day, the efficiency of some solar cells may drop as the equipment's temperature increases, reducing PV output. Wind output also tends to be lower during the day and peaks at night when load is the lowest. This attribute favors the use of energy storage to increase the capacity factor of wind turbines. Figure 5.5 illustrates the mismatch between load and renewable generation due to diurnal intermittency. The average daily profiles of wind and solar were modeled assuming 23% wind and solar penetration in the Western Electricity Coordinating Council (WECC). Since wind and solar ramps are usually inversely correlated in the morning and evening, integrating both wind and solar power may reduce load-following and regulation requirements during some hours of the day.

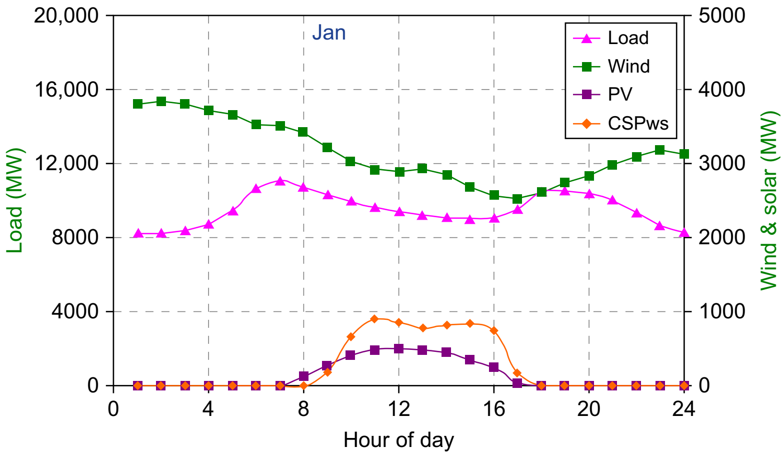

FIGURE 5.5 Arizona load, wind, and solar average daily profiles for January. *(Source: Western Wind and Solar Integration Study, May 2010 (NREL/SR-550-47434))*

Voltage Regulation Problems

The sources of intermittency discussed above that lead to variable PV and wind output can cause potential problems in the reliability and stability of the electric power system, such as in frequency and voltage regulation, load profile following, and broader power balancing. Entities such as the California ISO (CAISO) and the New York State Energy Research and Development Authority (NYSERDA) have conducted studies on issues surrounding the integration of renewable energy. For a 20% wind penetration scenario, CAISO found that all wind generation units should meet the WECC requirements of ±0.95 power factor. This dynamic reactive capability is necessary for voltage control to ensure system stability [15]. NYSERDA also found that wind power needed to meet Low-Voltage Ride Through standards and voltage regulation criteria even at only 10% penetration levels [16]. Both studies found that accurate day-ahead and hour-ahead forecasts of wind and solar generation are essential for reliable operation of the power grid and scheduling of other generation resources and unit commitment, with solar playing a larger role as California moves toward a 33% renewables portfolio standard (RPS) by 2020.[2]

When transients are high, area regulation will be necessary to ensure that adequate voltage and power quality are maintained. Advanced PV system technologies, including inverters, controllers, and balance-of-system and energy management components, are necessary to address voltage regulation issues. At high PV penetration levels, the RSI report on "Distributed Photovoltaic Systems Design and Technology Requirements" suggests that the problems most likely to be encountered are voltage rise, cloud-induced voltage regulation issues, and transient problems caused by mass tripping of PV during low voltage or frequency events [17]. This report discusses several studies where the maximum PV penetration level was found to be anywhere from 25% to 50% before voltage regulation became a problem.

The smart grid integrated with PV and wind will need to have two-layered voltage regulating capabilities from a speed-of-response perspective. Slow regulation (for managing distribution system voltage profiles or microgrid operation[3]) and fast regulation (for addressing flicker and cloud-induced fluctuations) will both be needed in high-penetration scenarios. The low-speed system responds as needed over a period of many tens of seconds or minutes to hold steady-state voltage within the ANSI limits. The second layer is a high-speed system on top of the slow-speed system and serves to moderate rapid changes in voltage and power that result from fluctuating wind and solar resources.

A PV inverter or associated energy storage system could provide voltage regulation by sourcing or sinking reactive power. Implementing this feature

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[2] Chapter 6 of this text also covers these issues.

[3] Chapter 8 of this text covers microgrids in more detail.

would require modifications to the traditional PV inverter hardware design and current interconnection requirements need to evolve.[4] During a workshop held by the DOE on the "High Penetration of PV Systems into the Distribution Grid" in February 2009, energy storage was identified as a possible solution to solar variability and intermittency; development of small- to mid-scale energy storage solutions was identified as a top RD&D activity. As discussed in section "Energy Storage for Integration," energy storage can be used for power management as an intermediary between variable resources and loads.

Capacity Firming

When PV and wind outputs are low, some type of back-up generation will be needed to ensure that customer demand is met. To address the issues of load profile following and power balancing, renewables capacity firming to decrease variable output needs to occur. Capacity firming offsets the need to purchase or build additional dispatchable capacity. Energy storage can be combined with renewable energy generation to produce constant power. Depending on the location, firmed renewable energy output may also offset the need for T&D investment. Renewables capacity firming is especially valuable when peak demand occurs, and energy storage can even be used for peak shaving.

Intermittent renewable generation is currently mitigated by ramping conventional reserves such as thermal plants up or down based on minute-by-minute and hourly forecasts. A CAISO study found that under the 20% RPS, dispatchable generators need to start and stop more frequently. In particular, combined-cycle generators' starts will increase by 35% compared to a reference case that assumes no new renewable capacity additions beyond 2006 levels [18]. Grid-scale energy storage would provide significantly faster response times than conventional generation, on the order of milliseconds versus minutes. Furthermore, a study by the California Energy Storage Alliance found that the levelized cost of generation for energy storage can be less than that for a simple cycle gas-fired peaker [19].

Therefore, as renewable penetration grows, energy storage will likely become more cost effective and necessary. Most studies conclude that traditional planning and operational practices only suffice for up to 10–15% renewable penetration levels. Although small penetrations of renewable generation on the grid can be smoothly integrated, accommodating more than approximately 20–30% electricity generation from these renewable sources will require new approaches in power system planning and operation. Storage can reduce the amount of dispatchable generation capacity needed to offset ramping of renewable energy generation. Therefore, capacity firming is valuable as a way to reduce load-following resources and improve asset utilization.

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[4] IEEE 1547 Standard for Interconnecting Distributed Resources with Electric Power Systems.

Storage power and discharge duration for renewables capacity firming are application- and resource-specific. At the lower end, it is assumed that one-half to as much as two hours of discharge duration are needed to firm solar generation, assuming that much of PV output coincides with peak demand, whereas to firm wind generation, a somewhat longer discharge duration of two to three hours is needed. Furthermore, the storage technology used for capacity firming should be reliable so as to provide constant power. The estimated 10-year net benefits associated with firming of PV and wind output are $709/kW and $915/kW, respectively [20].

ENERGY STORAGE FOR INTEGRATION

Energy storage for capacity firming can also minimize curtailment of renewable generation through maximizing energy harvest. As mentioned earlier for energy management applications, storage can also offset the need for additional generation or reserve capacity by continuing to supply power during cloudy or nighttime conditions and addressing power demand surges. Other benefits of energy storage that enable the integration of higher levels of renewable generation include peak shaving or price arbitrage, that is, storing energy during low demand and delivering it back to the grid during peak demand. Stored energy and storage capacity would be managed most effectively with a control algorithm that takes into account estimates of future hourly pricing and renewable generation output. The CAISO Integration of Renewable Resources study modeled regulation and load-following requirements under a 20% RPS, which includes approximately 9 GW of wind and solar power in California. The simulations indicated that the maximum regulation-up requirement will increase 35%, from 278 MW in 2006 to 502 MW in 2012. The maximum hourly simulated load-following up requirement in 2012 is 3737 MW compared to 3140 MW in 2006 [18].

Applications and Technologies

The grid applications for energy storage technologies can be loosely divided into power applications and energy management applications, which are differentiated based on storage discharge duration. Energy applications discharge the stored energy relatively slowly and over a long duration (i.e., tens of minutes to hours). Power applications discharge the stored energy quickly (i.e., seconds to minutes) at high rates. Storage technologies for power applications are used for short durations to address power quality issues, such as voltage sags and swells, impulses, and flickers. The use of storage to prevent voltage rise from the export of power from the customer facility to the grid has been demonstrated in Japan's Ota City PV-integrated distribution system.[5] Technologies used for energy management applications store excess electricity during periods of low

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[5] Ueda Y. et al., "Performance Ratio and Yield Analysis of Grid-Connected Clustered PV Systems in Japan." In Proceedings of the 4th World Conference on Photovoltaic Energy Conversion, pp. 2296–99.

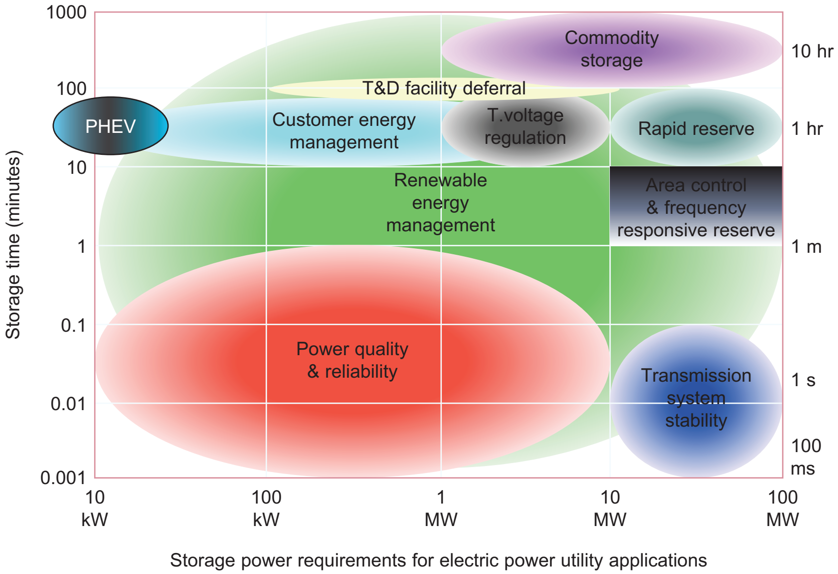

FIGURE 5.6 Energy storage applications and their associated power and discharge duration requirements. *(Data from Sandia Report 2002–1314)*

demand for use during periods of high demand. These devices are typically used for longer durations to serve functions that include peak shaving, load-leveling, intentional islanding, and renewable energy collection and dispatch. Figure 5.6 illustrates the storage power and discharge duration requirements as a function of application.

Current grid-scale energy storage systems are both electrochemically based (batteries and capacitors) and kinetic energy based (pumped hydropower, compressed-air energy storage [CAES], and high-speed flywheels). For power applications, suitable technologies include flywheels, capacitors, and superconducting magnetic energy storage. For energy applications, suitable technologies include pumped hydropower, CAES, and high-energy sodium-sulfur and flow batteries. The batteries in electric vehicles can also be used for both energy and power applications; they can provide energy management services through controlled charging during off-peak periods, thereby reducing curtailment of wind power, and frequency regulation through vehicle-to-grid capabilities. Such charging schemes would be based on smart grid communication of real-time load, price, and renewable energy generation.[6]

Thermal storage is built into CSP and is also gaining ground on the customer side in the form of heating in sustainable building mass and cooling via

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[6] More details on linking the charging of electric vehicles to price signals can be found in Chapters 18 and 19.

phase-change systems. Since heating, ventilating and air conditioning are the largest contributors to peak energy demand, thermal energy storage for storing off-peak power and shifting electricity used for air conditioning is becoming popular in commercial buildings. Distributed thermal storage is mainly used for lowering peak demand and shaping load, and needs to be combined with an electric utility's demand response program for maximum benefits. This chapter focuses instead on storage technologies for dispatchable generation.

These technologies for specific applications can be further subdivided according to the scale of storage required, for instance, deployment as a distributed energy resource, or at the distribution feeder, substation, or bulk power system level. Energy storage in a future system will likely be needed in a variety of sizes and configurations to meet needs at all system levels. The wide range of mechanisms, chemistries, and structures of these energy storage technologies enables them to be tailored to meet the power and energy demands of specific applications. Figure 5.7

Technology option	Maturity	Capacity (MWh)	Power (MW)	Duration (hrs)	% Efficiency (total cycles)	Total cost ($/kW)	Cost ($/kW-h)
Bulk energy storage to support system and renewables integration							
Pumped hydro	Mature	1680–5300	280–530	6–10	80–82 (>13,000)	2500–4300	420–430
		5400–14,000	900–1400	6–10		1500–2700	250–270
CT-CAES (underground)	Demo	1440–3600	180	8	See note 1 (>13,000)	960	120
				20		1150	60
CAES (underground)	Commercial	1080	135	8	See note 1 (>13,000)	1000	125
		2700		20		1250	60
Sodium-sulfur	Commercial	300	50	6	75 (4500)	3100–3300	520–550
Advanced Lead-acid	Commercial	200	50	4	85–90 (2200)	1700–1900	425–475
	Commercial	250	20–50	5	85–90 (4500)	4600–4900	920–980
	Demo	400	100	4	85–90 (4500)	2700	675
Vanadium redox	Demo	250	50	5	65–75 (>10000)	3100–3700	620–740
Zn/Br redox	Demo	250	50	5	60 (>10000)	1450–1750	290–350
Fe/Cr redox	R&D	250	50	5	75 (>10000)	1800–1900	360–380
Zn/air redox	R&D	250	50	5	75 (>10000)	1440–1700	290–340
Energy storage for ISO fast frequency regulation and renewables integration							
Flywheel	Demo	5	20	0.25	85–87 (>10000)	1950–2200	7800–8800
Li-ion	Demo	0.25–25	1–100	0.25–1	87–92 (>100,000)	1085–1550	4340–6200
Advanced lead-acid	Demo	0.25–50	1–100	0.25–1	75–90 (>100,000)	950–1590	2770–3800

FIGURE 5.7 Energy storage characteristics by application. *(Source: Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI, Palo Alto, CA, 2010. 1020676. © 2010 Electric Power Research Institute, Inc. All rights reserved)*

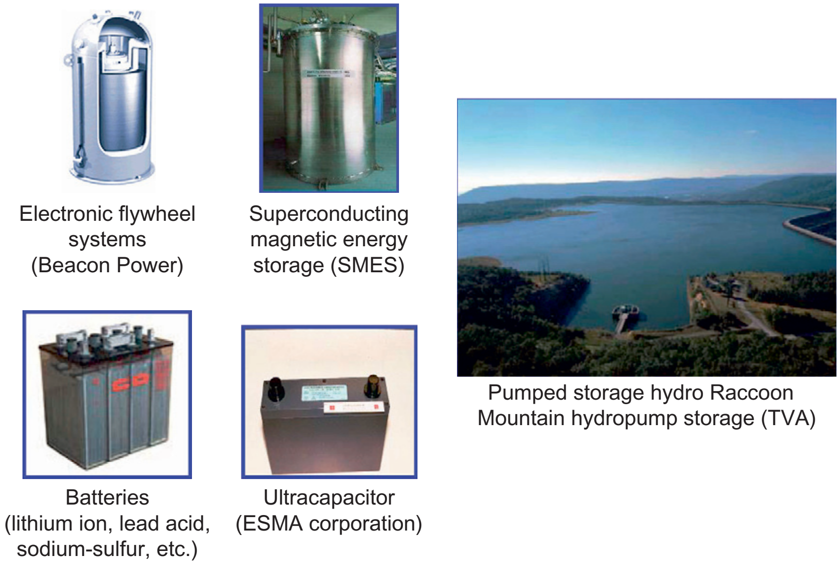
Note 1: Refer to the full Electric Power Research Institute (EPRI) report for important key assumptions and explanations behind these estimates.

tabulates the main characteristics including size, performance, and cost of these storage technologies according to their power or energy application for renewables integration.

Centralized storage, such as pumped hydropower and CAES, is most likely to be applied at the supply side, (i.e., transmission or bulk system level), to manage variations in output from solar plants and wind farms via capacity firming. Pumped hydropower uses off-peak electricity to pump water from a low-elevation to a high-elevation reservoir. The stored energy is delivered to the grid by releasing the water through turbines to generate power. The United States has pumped hydropower facilities in 19 states that provide about 23 GW of capacity. Out of all the energy storage options, pumped hydropower is the most established technology; however, it has a higher capital cost compared to CAES. CAES uses off-peak power to pump air into a storage reservoir such as an underground salt cave. The air is released through a turbine to meet power demand. As seen in Figure 5.7, underground CAES is the cheapest bulk energy storage option. However, lack of data and analysis on suitable sites has limited its use. The United States has only one 110-MW CAES plant in Alabama. A barrier to both pumped hydropower and CAES development is assessment of resource availability. While pumped hydropower has achieved widespread deployment, all of the suitable locations currently being used provide only a small fraction of baseload electricity needs.

At the distribution level and the customer-distributed resource location, more compact and short-duration forms of energy storage for power applications (batteries, flywheels, and capacitors) are more likely to be used. Superconducting magnetic energy storage (SMES) is an experimental technology that may also be used for power applications. The different storage technologies are shown in Figure 5.8. The use of batteries, flow batteries, flywheels, and ultracapacitors for power applications has gathered considerable steam in recent years as they are well suited for rapid compensation of power fluctuations from wind and PV. In fact, many recent distribution-scale demonstration projects have successfully established the value of these technologies for frequency regulation, intentional island transitioning, and other such applications. Such distributed storage technologies serve the demand side; these mobile, modular technologies are preferred for microgrids and off-grid communities.

The RSI study on “Enhanced Reliability of Photovoltaic Systems with Energy Storage and Controls” observed a significant improvement in the three reliability indices—critical SAIDI (average duration of critical load interruptions), critical SAIFI (average number of interruptions per customer), and unserved critical load (UCL, annual unserved critical load [kWh] on a circuit)—when PV and battery energy storage were deployed at each home within a community. The presence of more than ~5 kWh of battery capacity per home reduced each index to nearly zero [21]. In order to reap maximum benefits from power management applications, the storage technology needs to have a



Electronic flywheel systems (Beacon Power)

Superconducting magnetic energy storage (SMES)

Pumped storage hydro Raccoon Mountain hydropump storage (TVA)

Batteries (lithium ion, lead acid, sodium-sulfur, etc.)

Ultracapacitor (ESMA corporation)

FIGURE 5.8 Various energy storage technologies. *(Source: Whitaker et al. [17] (SAND2008-0944 P))*

roundtrip efficiency of 75–90%, a system lifetime of 10 years with high cycling, a capacity of 1 MW to 20 MW, and a response time of 1 to 2 seconds [22].

For most PV applications, lead-acid technology has been the preferred energy storage technology due to its maturity, low cost, and availability. However, its low energy density, short cycle life, and high maintenance requirements have deterred wide-scale use in the electric grid. A number of lead-acid battery manufacturers, such as East Penn in the United States and Furukawa in Japan, are manufacturing prototype batteries for hybrid electric vehicles to overcome the main disadvantages of valve-regulated lead-acid (VRLA) batteries by using new carbon formulations for the anodes. These formulations promise to reduce sulfation, thereby increasing the cycle life and available energy. Before applying such technologies to the grid, however, a better understanding is needed of how particular applications such as peak shaving will affect the battery life.

Other advanced technologies such as molten salt batteries are currently being developed for utility-scale (> 1MW) applications. For instance, sodium-sulfur batteries have high energy density and are low cost; however, high operating temperatures between 300 to 350°C limit their use. Other molten salt batteries such as sodium/nickel-chloride, or ZEBRA batteries, have been developed for transportation applications and are currently being considered for some grid-scale applications, such as peak shaving. Figure 5.9 groups the major energy storage technologies according to their suitability for certain applications.

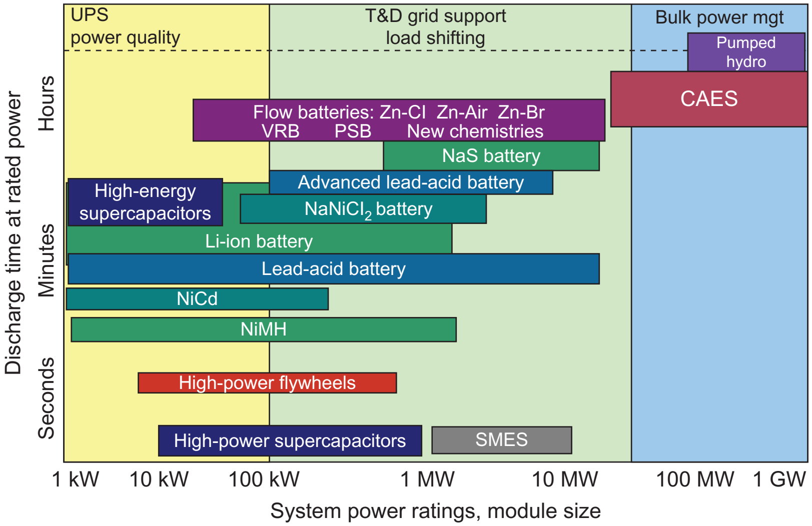


FIGURE 5.9 Energy storage technologies according to specific application power and discharge duration requirements. *(Source: Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI, Palo Alto, CA, 2010. 1020676. © 2010 Electric Power Research Institute, Inc. All rights reserved)*

Cost-Benefit Analysis

The main issues preventing widespread deployment of these energy storage technologies are the current high capital cost (Figure 5.10) and market structure that make it difficult to quantify and capture all of their value streams across the electric grid. Aggregated benefits are not accounted for, cost recovery is complicated by the regulatory vacuum in terms of how to categorize energy storage as an asset, (i.e., as transmission, distribution, generation, or load), and there is a lack of communication to electric utilities that energy storage is more economical than gas-fired peakers. These barriers result in underinvestment in energy storage despite its social and economic benefits [15].

With the exception of pumped hydropower and perhaps CAES, the other energy storage technologies are expensive options. As a result, they are not widely used on a large-scale commercial basis for long-duration applications, which require several hours of power output at the storage device's rated power capacity. For arbitrage and load-following applications, the target capital cost for commercialization is \$1,500 per kW or \$500 per kWh, with an operations and maintenance cost of \$250–\$500 per MWh for a discharge duration of 2 to 6 hours [22]. These requirements mean that costs need to be lowered for technologies such as lithium-ion batteries, electrochemical capacitors, and advanced flywheels for grid-scale applications. Placement flexibility could be important for the economics of energy storage given

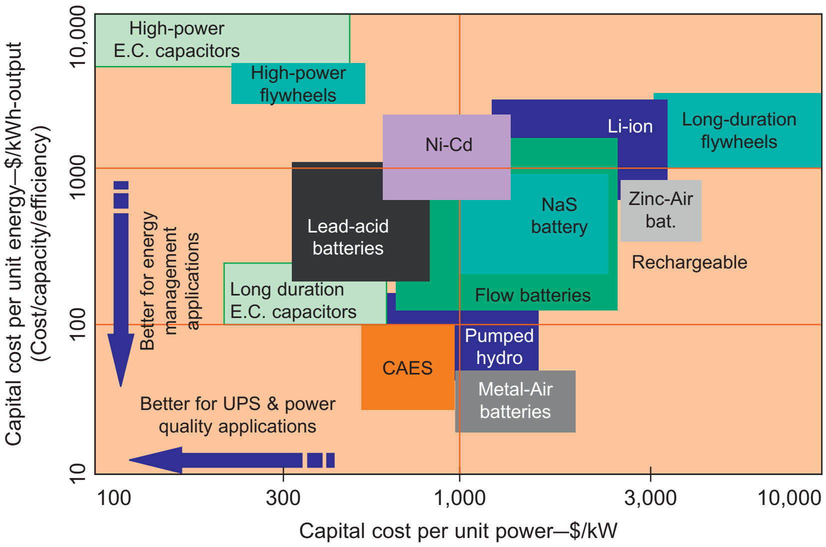


FIGURE 5.10 Capital cost of various energy storage technologies. *(Source: Electricity Storage Association, http://www.electricitystorage.org/ESA/technologies/)*

that electrochemical storage devices are not constrained to a specific geographic topology and hydrological system, unlike CAES and pumped hydropower systems.

With the growing contributions of intermittent energy resources across the United States, load-balancing requirements are expected to grow. A Pacific Northwest National Laboratory (PNNL) study has estimated the balancing requirements for the 2019 timeframe under a 14.4 GW wind scenario in the Northwest Power Pool (NWPP). This study examined various scenarios for meeting balancing requirements using an array of technologies, including sodium-sulfur and lithium-ion batteries, combustion turbines, demand response, and pumped hydropower. The main insights were that sodium-sulfur was the least costly option whereas pumped hydropower was the most costly option, and that storage should be able to accommodate ~25% of projected 2019 wind generation for the NWPP.

These results indicate that energy storage, and particularly electrochemical storage, technologies can compete with conventional combustion turbines when used to meet specific load-balancing requirements with high ramp rate requirements. This finding has general applicability beyond the investigated NWPP footprint [23].

Energy arbitrage opportunities, however, may not be the key driver for large deployment of energy storage, at least not in the near term, that is, 2010–2019. Results from a Sandia National Laboratories (SNL) analysis of the Pennsylvania, New Jersey, and Maryland (PJM) region indicated that arbitrage benefits for

Benefit type	Avg. gross benefit ($/kW-year)	Benefit capture (% of gross)	Net benefit ($/kW-year)
Electric supply			
Electric energy time-shift	77	50%	39
Electric supply capacity	75	100%	75
Ancillary services			
Load following	112		
Area regulation	195		
Electric supply reserve capacity	20	75%	15
Voltage support	56	50%	28
Grid operations			
Transmission support	27		
Transmission congestion relief	12	75%	9
T&D upgrade deferral, 50th percentile*	584*	100%	584*
T&D upgrade deferral, 70th percentile*	752*	100%	752*
T&D upgrade deferral, 90th percentile*	919*	100%	919*
Reliability (15 min. –1 hour)	93		
Power quality (10 seconds)	93	50%	47

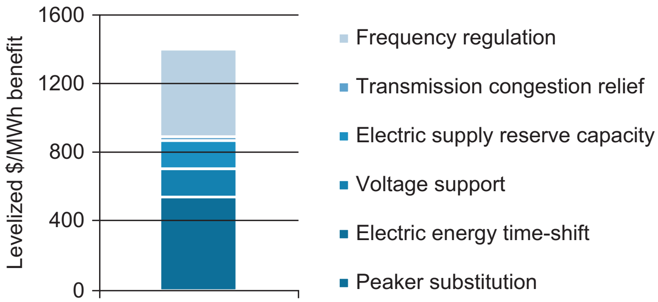


FIGURE 5.11 System benefits of energy storage according to application. *(Source: Eyer et al. [20] (SAND2010-0815))*

10 years of storage operation are on the order of $300/kW, whereas single-year T&D capacity upgrade deferrals are worth as much as $1000/kW of storage installed [24]. These numbers are consistent with those from a more recent SNL study covering the entire United States, summarized in Figure 5.11. These benefits appear to be additive in the case of application synergies, such as storage used for capacity firming, voltage support, and arbitrage [20]. Aggregating energy storage benefits will make a stronger case for their widespread deployment by increasing the benefit-to-cost ratio.

Figure 5.12 provides a perspective of the level of maturity based on installed capacity of grid-tied storage globally. These numbers suggest that there is significant room for cost and performance improvements of the less mature technologies such as compressed air and batteries, while pumped hydropower, due its maturity, is not likely achieve cost reduction—at least at the same rate as the nascent battery technologies. Research and development on energy storage systems, specifically batteries, are expected to lower their costs.

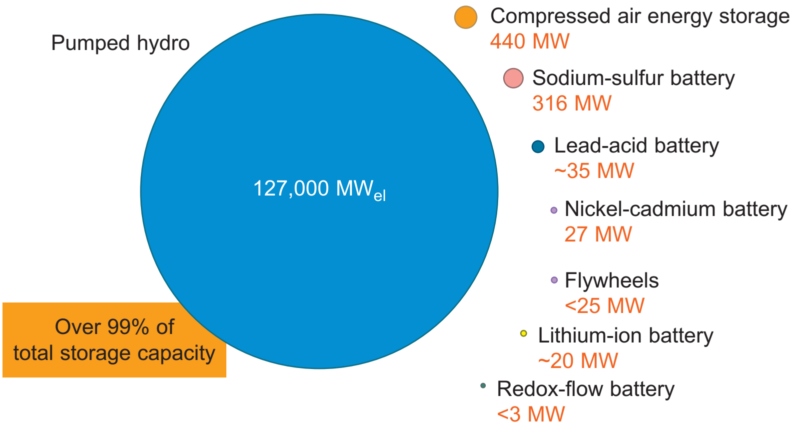


FIGURE 5.12 Worldwide installed storage capacity for electrical energy. *(Source: Electric Energy Storage Technology Options: A White Paper Primer on Applications, Costs, and Benefits. EPRI, Palo Alto, CA, 2010. 1020676. © 2010 Electric Power Research Institute, Inc. All rights reserved)*

R&D Directions

Successful development of renewable energy storage systems will require comprehensive systems analysis, including economic and operational benefits and system reliability modeling. Systems should be analyzed based on the requirements of the application. The analysis should include an investigation of all of the possible storage technologies suitable for the application and the operational/cost/benefits tradeoffs of each. R&D is needed to quantify the value of energy storage to the grid depending on the application, and economic viability needs to be assessed by comparing value to the lifecycle cost. Models for analysis of energy storage value as a function of time, location, market, solar profile, etc, need to be developed. Software-based modeling and simulation tools represent a key component of successful systems analysis. For instance, the Regional Energy Deployment System (ReEDS) model[7] developed at NREL was used to quantify the value that storage can add to wind under the 20% penetration scenario in the “20% Wind by 2030” report.[8] ReEDS integrates storage technologies such as CAES, pumped hydropower, and batteries with renewable generation such as wind and solar.

Besides systems analysis, control algorithms to optimize application of energy storage and enable real-time dispatch need to be developed. For electrochemical storage, advanced battery management systems can be developed to address some of the charge/discharge issues. The U.S. Coast Guard is sponsoring an effort to develop the Symons Advanced Battery Management System

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[7] http://www.nrel.gov/analysis/reeds/.
[8] http://www.20percentwind.org/.

(ABMAS) for off-grid, PV-storage-generator hybrid systems. Initial results using the ABMAS system show a 25% reduction in fuel use and improved battery charging and discharging profiles, thus promising increased battery lifetime.[9] Similar management systems are needed for grid-connected PV-storage systems and applications.

By themselves, energy storage devices (batteries, flywheels, etc.) do not discharge power with a 60-Hz AC waveform, nor can they be charged with 60-Hz AC power. Instead, a power conditioning system is necessary to convert the output. Under the SEGIS initiative, the DOE Solar Energy Program is currently developing integrated power conditioning systems for PV systems. These systems include inverters, energy management systems, control systems, and provisions for including energy storage. It is anticipated that charging and discharging control algorithms for different battery technologies will be included in the SEGIS control package.

The main R&D needs for battery technologies address the following aspects of their use:

- Increasing power and energy densities;
- Extending calendar- and cycle-life;
- Increasing efficiency;
- Increasing reliability;
- Ensuring safe operation; and
- Reducing costs.

FEDERALLY FUNDED ENERGY STORAGE EFFORTS

Several programs at the Department of Energy are funding energy storage research for both grid-scale and transportation applications. Federal support for stationary energy storage mainly stems from the Office of Electricity (OE), which funds projects to improve basic materials for battery, electrolytic capacitor, and flywheel systems to reduce cost and enhance capabilities, improve the modeling capabilities of compressed-air energy storage, and develop advanced components and field-test storage systems in diverse applications.

The Renewable and Distributed Systems Integration (RDSI) program within the OE focuses on integrating renewable energy, distributed generation, energy storage, thermally activated technologies, and demand response into the electric distribution and transmission system. This integration is aimed toward managing peak loads, offering new value-added services such as differentiated power quality to meet individual user needs, and enhancing asset use. The program goal is to demonstrate a 20% reduction in peak load demand by 2015, through increased use of both utility- and customer-owned assets.

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[9] Corey, G. "Optimizing Off-grid Hybrid Generation Systems." *EESAT 2005*, Conference Proceedings.

The American Recovery and Reinvestment Act (ARRA) allocated $185 M for deploying and demonstrating the effectiveness of utility-scale grid storage systems. The goal is provide a ten-fold increase in energy storage capacity to improve grid reliability and facilitate the adoption of variable and renewable generation resources. Three projects on large battery systems (total 53 MW) will address the variable nature of wind energy and aid in the integration of wind generation into the electric supply. The additional projects include two CAES (450 MW), one frequency regulation (20 MW), five distributed projects (9 MW), and five technology development projects.

Other ARRA-funded energy storage projects have been awarded by the Advanced Research Projects Agency–Energy (ARPA-E), which funds high-risk, translational research driven by the potential for significant commercial impact in the near-term. The funded projects under the "Grid-Scale, Rampable, Intermittent Dispatchable Storage (GRIDS)" topic area include nine battery (e.g., sodium-beta, liquid metal, flow batteries, metal-air), one SMES, two flywheel, one CAES, and one fuel cell.

The EERE also funds stationary energy storage projects through the SETP and Wind and Water Power Program, as discussed earlier in this chapter. SEGIS projects range from optimizing interconnections across the full range of emerging PV module technologies to lowering manufacturing costs through integrated controls for energy storage and development of new inverter designs. In the area of sustainable pumped storage hydropower, the DOE intends to provide $11.8 million in funding toward projects that begin construction by 2014 and integrate wind and/or solar.

The Office of Science also supports energy storage R&D through its Basic Energy Sciences (BES) program. The core program conducts fundamental research to understand the underlying science of materials and chemistry issues related to electrical energy storage. BES will be initiating a Batteries and Energy Storage Hub in FY 2011 with a planned funding amount of $35 million. This particular Energy Innovation Hub will address specific areas of research that were identified in the BES workshop report titled "Basic Research Needs for Electrical Energy Storage" that include efficacy of materials architectures and structure in energy storage, charge transfer and transport, electrolytes, multi-scale modeling, and probes of energy storage chemistry and physics at all time and length scales. Fundamental research on electrochemical storage technologies is also funded through Energy Frontier Research Centers across the United States.

CONCLUSIONS

As the fastest growing renewable energy sources worldwide, solar PV and wind power are gaining a stronghold in the electric grids of the United States and the world. The issues surrounding their intermittency need to be addressed so that this growth can be sustained, especially in the context of integration with smart grids that are being planned and deployed. Variations in energy output at 20–30% penetration levels of renewables may cause reliability problems in the electric grid, such as voltage fluctuations, and require a significant amount of reserves for capacity firming. The challenge of renewable resource intermittency can be met using a variety of energy storage technologies in lieu of conventional generators. The energy storage capacity for renewable generation varies from kW to hundreds of MW, depending on whether it will be used for power or energy management, (e.g., frequency regulation or capacity firming).

The optimal technologies for addressing renewable energy integration will be application-specific and will scale with the size of variable generation, ranging from pumped hydropower and CAES for centralized, bulk storage at PV plants and wind farms to batteries and electric vehicles for distributed storage near rooftop PV installations. The increasing amount of distributed renewables has triggered an evolution from centralized to distributed storage. Smart grid deployment is facilitating this transition since integration of distributed storage requires more intelligent control, advanced power electronics, and two-way communication. Both central and distributed energy storage are required for source-load matching in a smart grid with high levels of renewable penetration. A cost-benefit analysis needs to be done to determine whether certain storage applications should address the supply or demand side.

Key benefits of energy storage include providing balancing services (e.g., regulation and load following), which enable the widespread integration of renewable energy; supplying power during brief disturbances to reduce outages and the financial losses that accompany them; and serving as substitutes for transmission and distribution upgrades to defer or eliminate them. A smart grid is needed to maximize benefits from load shifting and ancillary services. To maximize these benefits and minimize costs, each energy storage technology needs to be optimized for certain applications. In particular, battery technologies are promising due to their wide range of chemistries and operating conditions for providing services that cover several applications. Over $380 million in federal funds are supporting energy storage R&D in the United States to lower their cost and improve performance.

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